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Dredged Material Plume Dispersal in Central Long Island Sound

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Dredged Material Plume Dispersal in Central Long Island Sound

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ABSTRACT: A simulation model based upon *in situ* current velocity data and records of disposal events was developed to predict the chemical exposure field resulting from dredged material disposal plumes in Central Long Island Sound (CLIS) during the spring of 1983. In the model, plumes are assumed to form as subthermocline suspended particulate clouds which are uniform vertically and Gaussian horizontally. Horizontal cloud dimensions are allowed to grow with a constant diffusion velocity as the plume is transported by tidal currents. The model permits estimation of increases or elevations in suspended solids concentration above background levels at individual sites resulting from multiple disposal operations. Model predictions of time-averaged elevations compare favorably with those estimated from tissue residues of *Mytilus edulis* deployed in CLIS as part of a joint Environmental Protection Agency (EPA)/Army Corps of Engineers program to investigate dredged material disposal options. Predicted elevations ranged between 0.0 and 1.6 mg/L. Based upon bulk chemistry measurements, a dredged material concentration of 1.5 mg/L translates to a water column polychlorinated biphenyl (PCB) concentration of approximately 10 ng/L, or about one third of the EPA chronic water quality criterion for that compound. The model indicates the contaminant exposure field at five biological effects field stations to be derived primarily from plume passage, rather than from postdisposal transport from a nearby disposal mound, during the period of active dredged material disposal. Both near (<1 km) and far (>1 km) field dispersal of dredged material in the form of plumes is indicated to occur within this shallow marine system.

KEY WORDS: plumes, dredged material, Long Island Sound, polychlorinated biphenyls (PCBs), particles, dispersion model, simulation, turbidity, currents, *Mytilus edulis*, tissue residues, contaminant exposure field, transport, diffusion equation, aquatic toxicology

The high rates of sedimentation found in most marine harbors necessitate periodic dredging to maintain water depth and prevent shoaling. In addition to recreational and commercial boating, industrial and manufacturing activities are often associated with these waterways. Sediments removed during maintenance dredging may therefore contain elevated levels of organic and inorganic contaminants. Disposal of dredged sediments thus presents a problem which has been receiving increased attention. Potentially viable disposal options include transport to upland landfills, aquatic disposal, and using the material to create or expand marine wetlands.

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In 1982, the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers (COE) initiated a multi-year program to investigate the comparative risks associated with these disposal options [*1*]. The Field Verification Program (FVP) was designed to assess and field validate methodologies for the prediction of environmental impacts resulting from disposal of dredged materials. The COE was responsible for investigating the upland and wetland disposal options, whereas EPA's Environmental Research Laboratory—Narragansett (ERLN) investigated the aquatic disposal option.

The ERLN applied its risk (formerly termed hazard) assessment research strategy for ocean disposal [*2,3*] to the investigation of the aquatic disposal option. Risk assessment includes both characterization of the environmental exposure field resulting from disposal of the material (exposure assessment), and examination of biological effects resulting from exposure to the material of interest (effects assessment). A detailed exposure assessment involves development of process models to describe contaminant transport, transformation, and fate in the environment. Calibration and verification of these models requires the collection of physical, chemical, and biological data.

Black Rock Harbor, Connecticut, (Fig. 1) was the source of dredged material for use in the FVP. Between 26 April and 14 May 1983, approximately 55 000 m^3 of material dredged from this harbor were disposed at a predetermined location in the Central Long Island Sound (CLIS) disposal area (Fig. 1). The water depth in this area is a fairly uniform 20 m, with little variation in bottom topography. Greater than 88% of the variation in current velocity at the site is explained by the first four tidal harmonics [*4*], with primary flow in an east-west direction. Maximum current speeds approach 25 cm/s. The water column is stratified from April through October, displaying a sharp thermocline at a depth of approximately 8 m [*5*].

The FVP site (see Fig. 1) was chosen to be far removed from other active disposal sites in CLIS and to be unaffected by historic disposal activities in the area. Five sampling stations were established along the primary axis of current flow to examine biological effects resulting from the disposal operation: CTR was located at the center of the disposal mound; 200E, 400E, and 1000E were located 200, 400, and 1000 m east of CTR, respectively; and REFS, a reference station, was located approximately 3 km to the southwest of CTR. It was initially assumed that the disposal mound itself would be the sole source of environmental contamination occurring at these stations. As a corollary, it was additionally assumed that REFS would remain unaffected by the FVP disposal mound due to its distance from that site and the direction of prevailing water currents. However, evidence of temporally varying water column contamination at CTR and increased contaminant tissue residues of *Mytilus edulis* deployed at REFS as part of the study were detected prior to the disposal operation at the FVP site [*5*]. This information indicated potential passage of dredged material plumes created by concurrent disposal operations at other sites within the CLIS disposal area. Approximately 10^6 m^3 of dredged material were disposed in CLIS from March through June 1983. Detailed assessment of exposure conditions existing at the FVP biological effects stations therefore necessitated examination of the above mentioned assumptions and of the potential influence of concurrent disposal operations elsewhere in CLIS.

Here we present the results of simulations of the transport of dredged material disposed at the CLIS disposal area during the spring of 1983. The intent of this work was to determine whether disposal operations occurring elsewhere in CLIS could affect chemical exposure fields at the biological effects stations described above. Information gathered during the FVP concerning the physical characteristics of the dredged material and published estimates of initial plume composition and dimensions were used to simulate plume formation and dispersion. Current velocity data obtained from *in situ* instrumentation were used

FIG. 1—*Long Island Sound and the locations of Black Rock Harbor, the CLIS disposal area, and the FVP study site.*

to transport each plume. A comparison of model predictions with another estimate of suspended dredged material concentrations is presented and implications of the results obtained through use of the model are discussed.

Procedure

Model Development

A model was developed to simulate the transport and dispersion of dredged material plumes within CLIS during the spring of 1983. Plumes were assumed to form below the seasonal thermocline (at 8 m from the surface [*5*]) as a result of retention of fine particulates and dissolved components within the water column following gravitational descent of the material released from scows. Material within each plume was assumed to be distributed uniformly in the vertical dimension and normally in the horizontal dimensions. This material was treated as being completely conserved; no losses occurred due to settling or other physical and chemical processes. Predictions of suspended solids elevations above background levels resulting from the passage of disposal plumes are therefore to be considered as upper bound estimates for transport.

The initial mass of suspended particulates within each plume was determined by the volume of dredged material released from the scow. Dumping logs containing load volumes were maintained by inspectors on the disposal vessels and were obtained from the New England Div., COE. Concentrations were established by multiplying the volume of material by its density (2.46 g/mL) and adjusting for its water content (72.6%). Previous studies have reported estimates of the amount of disposed material remaining in suspension as ranging from 1 to 5% [*6,7,8*]; we chose a conservative value of 0.25% to account for the particulate material that would rapidly settle out and not be transported. For a typical scow load of 2675 m^3, approximately 4500 kg of material was calculated to remain in the water column.

The initial distribution of mass within the plume, and subsequent dispersion of this mass, was controlled by the solution to the diffusion equation [*9*]

$$C(x,t) = \frac{M}{\sqrt{2\pi}\,(\sigma + \omega t)} \exp\left[\frac{-x^2}{2(\sigma + \omega t)^2}\right]$$

where $C(x,t)$ is the mass concentration at time t at a distance x from the plume's center, M is the concentration of mass in the y and z dimensions, σ is the initial width of the plume, and ω is the constant diffusion velocity or plume growth rate. We used 50 m as our estimate of initial plume width based upon studies of a similar dredged material disposed of in CLIS [*6*], and a diffusion velocity of 0.3 cm/s [*10*]. Distribution of a suspended mass of 4500 kg resulted in a peak suspended dredged material concentration of 60 mg/L at the plume's center.

The dumping logs also provided information concerning the approximate timing and location of individual scow releases. In addition to the FVP site, four other dump sites (denoted MQR, CS-1, CS-2, and SP) were actively used during the spring of 1983. Their locations relative to the FVP site and the biological effects stations are shown in Fig. 2. Individual scow releases at a specific disposal site generally occurred within a 200-m radius of that site's marker buoy. This uncertainty in disposal location was not incorporated into the model; all releases at an individual site were assumed to have taken place at the buoy.

Current velocity data used to transport plumes in the simulation were obtained from an electromagnetic current meter deployed in near-continuous fashion at the 1000E station

FIG. 2—*Locations of active disposal sites and biological effects stations in CLIS.*

during spring 1983 [*11*]. Horizontal velocities at 1 m above the bottom were burst sampled at 15 min intervals. For the purposes of this simulation, currents were assumed to be coherent over the entire study area and were represented by those measured at 1000E. The uniform topography and water depth of the study area suggest this assumption to be valid. Data from three deployments (NHDB09, NHDB10, and NHDB11) of the *in situ* current meter were used (see Table 1). These deployments bracketed the disposal operations at the FVP site (26 April to 14 May) and corresponded to periods of high disposal activity and dynamic changes in water column chemical exposures [*5*].

Model Behavior

Because of the *a posteriori* nature of this analysis, the model was not validated through field studies. Model behavior was therefore examined through a comparison with data collected independently as part of the FVP. Predictions of time-averaged exposures to the dredged material were compared with estimates derived for tissue residues of *Mytilus edulis* (blue mussels) deployed at 1 m above the bottom at each of the biological effects stations [*12*]. *Mytilus* deployment periods are given in Table 1. A laboratory-derived regression (see below) was used as a calibration line [*13*] to predict the concentrations of Black Rock Harbor (BRH) material sufficient to produce the tissue concentrations observed in the field over similar exposure times. It was assumed that *Mytilus* provided an integrated measure of water column exposure conditions. Laboratory studies [*12*] support this assumption.

Much of the material disposed in CLIS had been dredged from harbors other than Black Rock Harbor. Because we lacked information concerning the chemistry of this material, it was necessary to assume the bulk chemistry of BRH to be representative of all material disposed in CLIS during the study. Additionally, it was necessary to restrict the comparison to contaminants whose behavior would not be greatly affected by physical, chemical, and biological differences between the laboratory and field exposures. We chose to examine polychlorinated biphenyls (PCBs), conservative contaminants found in high levels (6.5 $\pm$ 0.4 μg/g dry weight [mean $\pm$ 1 standard error (SE)]) in the BRH-dredged material [*5*], for this comparison. Total PCBs were quantified as Arochlor 1254. The calibration line for PCBs was PCB residue = 1036.3 $\times$ BRH concentration + 282.0 (R^2 = 0.999; see Ref *12*).

Results

Model Behavior

The behavior of the simulation model can best be visualized by examining the results of a single disposal event. Figure 3 shows the first 12.5 h (one tidal cycle) of the predicted trajectory of the center of a plume created at MQR after a scow release on 2 May at 13:35.

TABLE 1—*Designations and periods of coverage of* in situ *instrumentation and* Mytilus edulis *deployments.*

	Designation	Period of Coverage, 1983
Instrument deployments	NHDB09	18 April to 26 April
	NHDB10	26 April to 23 May
	NHDB11	23 May to 16 June
Mytilus edulis deployments	T+0	22 April to 24 May
	T+2	23 April to 7 June

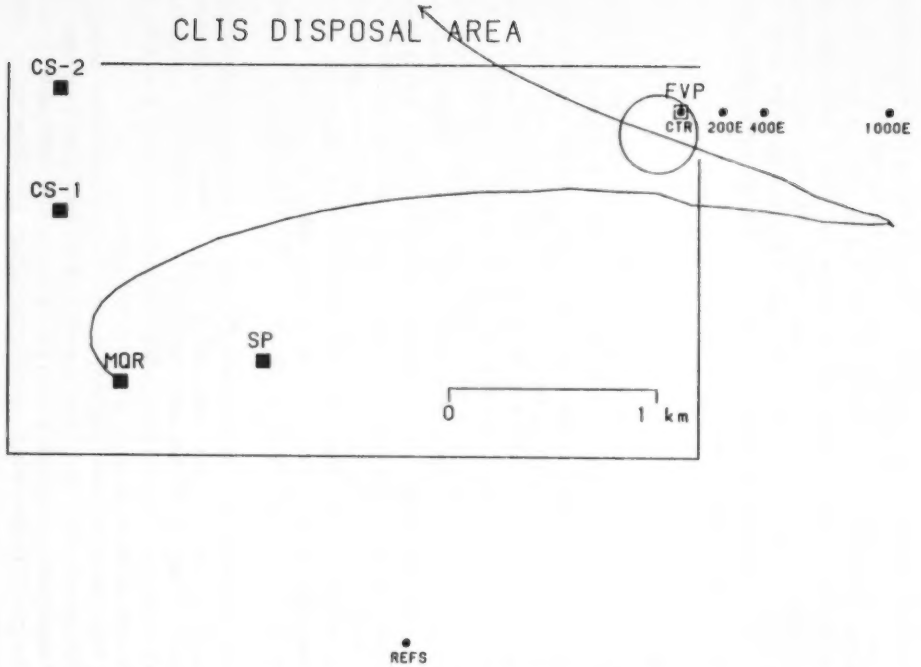

FIG. 3—*Predicted trajectory of the center of a disposal plume created at MQR on 2 May. The disposal occurred at 13:35, shortly before high tide. The circle centered about the trajectory near CTR corresponds to the 10 mg/L isoconcentration predicted at that time.*

This disposal occurred shortly before high tide. After a brief excursion to the northwest, the plume was transported to the east on an ebb tide, resulting in its passage near the biological effects stations. The following flood tide brought the plume to within 150 m of CTR before being transported out of the area. In Fig. 3, the circle centered about the trajectory near CTR corresponds to the predicted 10 mg/L isoconcentration of the plume at that time. The plume's passage resulted in a sharp elevation in suspended solids of approximately 12 mg/L as shown in Fig. 4 (*top*). The temporal pattern of suspended solids elevations resulting from all disposal operations during the NHDB10 deployment of the *in situ* current meter is shown in Fig. 4 (*bottom*). Fifty-nine strong (>5 mg/L) peaks were predicted to occur as a result of the 149 dumping events during this period.

Time-averaged suspended solids elevations predicted to occur at 400E, 1000E, and REFS during the two *Mytilus* deployments are given in Table 2. BRH concentrations required to produce the PCB tissue residues observed in *Mytilus* deployed during these periods are also given in this table (residue data were not collected at CTR or 200E during either deployment). Predicted dredged material concentrations are generally similar to those derived from the residue data.

Model Results

Model predictions of time-averaged dredged material concentrations resulting from operations at all five active disposal sites are given in Table 3. In general, average elevations fell between 0 and 1.5 mg of dredged material per litre. A graded exposure from CTR (high) to 1000E (low) was predicted for deployments NHDB09 and NHDB10, whereas the opposite trend was predicted for NHDB11. Relative to background suspended solids concentrations of 15 mg/L [*14*], these elevations appear trivial and would probably be undetectable on a time-averaged basis. However, a BRH concentration of 1.0 mg/L translates to a water column PCB concentration of approximately 6.5 ng/L. As background levels of PCBs in CLIS were determined to be on the order of 0.3 to 0.5 ng/L during spring 1983 [*5*], the predicted increase in water column contamination resulting from plume transport is significant. In addition, *Mytilus* displayed negative physiological responses to BRH concentrations as low as 1.5 mg/L (the lowest level tested) in related laboratory tests [*12*]. It should be noted that a BRH concentration of 1.5 mg/L translates to a water column PCB concentration of about 10 ng/L, or about one third of the EPA chronic water quality criterion [*15*].

The relative contribution of disposal at the FVP site to overall exposure conditions at the biological effects stations is also indicated in Table 3. When model conditions were restricted to scow releases at that site only (during deployment NHDB10), predicted time-averaged concentrations of suspended dredged materials were only 12 to 50% of those obtained when operations at all active sites were considered.

Relatively large elevations were predicted to occur at the REFS station during deployment NHDB09, prior to the FVP disposal operation. Additionally, plume passage was predicted to influence water column chemistry at CTR during this deployment. These results agree with the pre-FVP contamination discussed earlier, providing further support of model predictions.

Discussion

The results of these simulations indicate that disposal operations unassociated with the FVP study may have influenced the chemical exposure fields experienced by biota at the FVP biological effects stations. The relative contribution of these distant disposal opera-

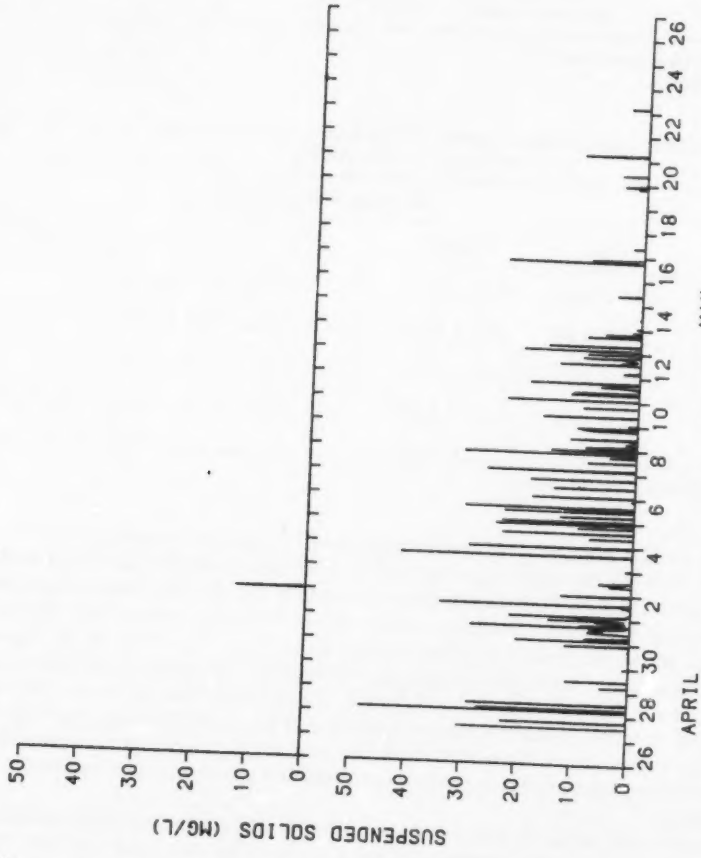

FIG. 4—*Temporal record at CTR of predicted suspended solids elevations above background resulting from a single scow release at MQR on 2 May* (top), *and from all disposal activities during the NHDB10 deployment of the* in situ *current meter* (bottom).

TABLE 2—*Comparison of predicted suspended dredged material elevations (in milligrams per litre) with dredged material exposures estimated from* Mytilus *tissue residues (in milligrams per litre).*

Mytilus Deployment		Biological Effects Station		
		400E	1000E	REFS
T+0	model prediction	...	0.42 ± 0.08[a]	0.0
	residue estimate	NC[b]	0.50 ± 0.07	0.0
T+2	model prediction	0.97 ± 0.02	1.01 ± 0.02	0.01 ± 0.00
	residue estimate	0.85 ± 0.06	0.44 ± 0.07	0.0

[a] Mean ±95% confidence interval.
[b] Data not collected.

TABLE 3—*Predicted time-averaged suspended dredged material elevations (in milligrams per litre) at biological effects stations.*

Deployment Period	Biological Effects Station				
	CTR	200E	400E	1000E	REFS
NHDB09 (all sites)	0.29 ± 0.14[a]	0.22 ± 0.12	0.13 ± 0.08	0.02 ± 0.02	0.61 ± 0.12
NHDB10 (all sites)	0.81 ± 0.14	0.68 ± 0.12	0.55 ± 0.10	0.42 ± 0.08	0.0
NHDB10 (FVP site)	0.37 ± 0.12	0.27 ± 0.10	0.17 ± 0.08	0.05 ± 0.04	0.0
NHDB11 (all sites)	1.06 ± 0.08	1.19 ± 0.08	1.33 ± 0.08	1.60 ± 0.10	0.02 ± 0.00

[a] Mean ±95% confidence interval.

tions was potentially large, as indicated by model results when scow releases were restricted solely to the FVP site during deployment period NHDB10 (Table 3). The initial assumption in the project that the FVP disposal mound would be the sole source of contamination is therefore suspect. Indeed, elevations in contaminant levels (as estimated by *Mytilus* tissue residues) during the period of active disposal in CLIS can be attributed for the most part to plume passage, rather than contaminant transport from the disposal mound itself. This general result has implications in regard to the risk associated with the disposal of contaminated materials in shallow marine systems. Further theoretical and empirical work is needed for evaluation of the relative contributions of plume passage and postdisposal transport of contaminants to the chemical exposure field experienced by organisms around disposal areas.

In addition to near-field (<1 km) influences, these results also suggest that disposal operations in shallow, high-energy marine systems such as CLIS may result in far-field (>1 km) transport of environmental contaminants. For instance, significant suspended solids elevations were predicted to occur at REFS during the NHDB09 instrument deployment period, when the nearest scow releases were approximately 1.5 km to the northeast (at SP, see Fig. 2). At this time, a more detailed assessment of the extent of lateral transport of dredged material cannot be determined by our model, as we assume complete conservation of plume constituents (that is, no gravitational settling by particles or loss due to other physical and chemical processes).

Some additional comments regarding model refinement and validation are cogent. The

model currently assumes a fixed percentage of the original mass released from the scow to remain in the water column as a plume. No regard is given to particle retention within the plume as related to particle size. Small particles generally settle more slowly than large particles and presumably display higher mass-specific contaminant concentrations due to an inverse surface area (with associated number of chemical "attachment sites") to volume relationship. Contaminant concentrations associated with the plume material may therefore be underestimated by the bulk chemistry of the material released. This error is confounded by the assumption of conservation of material within the plume during transport and dispersion. A more accurate estimate of chemical exposures at the biological effects stations would be achieved by incorporating information concerning both differential particle retention and settling and particle size specific chemistry into the plume formation and transport phases of the simulation. Ideally, aspects of contaminant phase partitioning could also be incorporated. With the collection of this type of information through empirical studies of the dredged materials, the model could also be used to predict off-mound benthic contamination associated with dredged material disposal.

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